

Challenges to Cabin Humidity Removal Presented by Intermittent Condensing Conditions

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ABSTRACT

On-orbit temperature and humidity control (THC) is more easily accomplished when the THC hardware is either consistently dry (i.e., no humidity control is occurring), or consistently wet. The system is especially challenged when intermittent wet/dry conditions occur. The first six years of on-orbit ISS operations have revealed specific concerns within the THC system, specifically in the condensing heat exchanger and the downstream air/water separator. Failed or degraded hardware has been returned to ground and investigated. This paper presents the investigation findings, and the recommended hardware and procedural revisions to prevent and recover from the effects of intermittent condensing conditions.

INTRODUCTION

The control of temperature and humidity in an enclosed environment presents particular challenges when applied under micro-gravity conditions. The removal of humidity is especially accommodated by gravity in earth-bound applications, but must be enabled using additional machinery when gravity is absent. In the case of the U.S. modules of the International Space Station (ISS), which utilize a Common Cabin Air Assembly (CCAA) to accomplish temperature and humidity control (THC), ground testing and analysis were particularly geared toward addressing conditions of maximum humidity production. This approach confirmed that the temperature and humidity could be controlled within required limits for reasonable maximum heat and humidity burdens within the respective ISS cabins. However, after six years of on-orbit operating experience, the greatest challenges experienced to date arise from low or intermittent heat and humidity loads.

The following report summarizes the issues surrounding intermittent condensing conditions within the air side of the ISS CCAA. Figure 1 shows a schematic cutaway of the CCAA, with the process air entering on the left and

exiting on the right. The air is drawn into the THC Return Ducting by the Inlet ORU (i.e., the fan), and then travels through either the Heat Exchanger (HX) or a bypass manifold (as diverted by the Temperature Control and Check Valve, or TCCV) as necessary to maintain the desired cabin temperature. The process air then passes across the temperature sensors and enters the downstream distribution ducting. The condensate from the HX is drawn into the Water Separator (WS), which separates the water from entrained air, and delivers it into a water bus (not shown). The entrained air is returned at the end of the CCAA just upstream from the distribution ducting.

[insert Figure 1]

Normally over the course of long-term operations, the objective is to operate a CCAA in condensing mode for about one month, and then to allow a dryout period for the sake of microbial control on the HX fins. For the central U.S. Laboratory Module (USL), where continuous THC operations are required, two CCAA's ("Port", and "Starboard") alternate their duty cycles to accommodate this long-term cycle. In the ISS Airlock (A/L), the need for THC is not continuous, which intrinsically accommodates the periodic dryout for microbial control. Thus, there is a certain, limited, quantity of wet/dry cycling which is intentional

Intermittent condensing conditions in the CCAA HX could also occur, for the most part unintentionally, if the humidity-control function is being accomplished elsewhere onboard ISS. This is often the case, as the preference to-date has been to control ISS humidity from the Russian Segment (RS). Under this operating regime, condensation might only occur sporadically in the USL or A/L CCAA's, particularly during periods of high latent loads.

Intermittent condensation within the CCAA HX also manifests itself as a periodic dryout in the CCAA Water Separator (WS). The concerns associated with periodic dryout (also called "wet/dry cycles") of the CCAA HX and

WS components are somewhat related, but the effects are different and involve different recovery approaches. Thus, the wet/dry phenomenon is addressed separately for these components as the data is interpreted and applied.

INTERMITTENT CONDENSATION; CAUSES, COMPLICATIONS, AND RECOVERY

CAUSES

Generally in an enclosed and inhabited environment, one would not expect intermittent periods of condensation within the dedicated air conditioner. With crews sleeping and working during common hours, it is expected that the humidity burden in the cabin would go through daily high and low periods, but humidity generation in the ISS environment would not completely stop at any point in time. However, with THC duties being shared amongst numerous hardware assemblies throughout ISS, and with significant mixing occurring between ISS modules via Intermodule Ventilation (IMV), there is a natural gravitation of humidity control toward the hardware with essentially the lowest setpoint. In the six-year history of manned ISS operations, this lowest setpoint has typically occurred within Russian THC hardware. This is deliberate, as it readily facilitates the transfer of condensate to the Russian water processing hardware for recycling.

Oftentimes onboard ISS, for periods of weeks or even months, all humidity control has been successfully accomplished in the RS. However, a number of factors might contribute to periods of condensing conditions within U.S. modules, specifically the A/L or USL. The temperature of water coolant flowing through the CCAA's might be reduced below local dewpoints, in order to support special equipment or operations relying upon the common Low Temperature Loop (LTL) for cooling. The air-exchange-rate between modules could drop significantly as IMV degrades or fails (or in the case of the A/L, the hatch could be closed with crewmembers inside), such that water vapor generated within a module would raise the dewpoint significantly within that same module. Also, there could be special activities or intense exercise which affects the dewpoint in a given module. Finally, the Russian THC hardware could experience degradation or be activated cyclically to accomplish some other purpose. All of these scenarios contribute to the reality that there are far more wet/dry cycles occurring within the U.S. CCAA hardware than originally envisioned.

The estimated progression of wet/dry cycles in each of the three on-orbit CCAA's over the six-year period of ISS operations is provided in Figure 2. The data in the figure is assumed to apply to both the HX and WS within each CCAA. However, as there is no direct sensing within the CCAA HX to indicate the presence or absence of condensing conditions, these conditions are often inferred. A Water Pressure Sensor is located within each CCAA WS, but because this sensor only detects

water after it surpasses a certain threshold, the exact wet/dry criteria is subject to some uncertainty (especially within the HX). Also, because the HX can retain considerable condensate before the condensate migrates along the assembly and into the WS, there could sometimes be a wet/dry cycle in the HX without an accompanying cycle in the WS. However, given the intrinsic limitations, there is enough evidence to suggest when conditions are wet and when they become dry, and a figure of the nature of Figure 2 is helpful to forecast possible problems if excessive wet/dry cycling is occurring.

[insert Figure 2.a.b.c]

INTERMITTENT CONDENSATION WITHIN THE HEAT EXCHANGER

Complications

The CCAA HX airside surfaces are coated with a hydrophilic agent to support the smooth flow of condensate along the fins and downstream to a series of flat plates called the "Slurper". The Slurper plates contain over 2000 pinholes (0.022" diameter) through which the condensate is drawn and manifolded to the WS. The HX hydrophilic coating is also impregnated with a biocidal silver compound, which is designed to protect the HX, along with the condensate and downstream water systems, from microbial presence. As such, the silver agent is designed to leach slowly into the condensate as it forms on the fins.

A variety of compounds from the hydrophilic coating and from the HX materials of construction find their way into the condensate. These numerous airborne volatile compounds which condense out on the HX or absorb into the condensate. Thus, if the HX is experiencing intermittent condensation, a number of metals and compounds can plate out or form a scale or powdery deposit on the HX airside surfaces where the condensate existed. This deposit can accumulate and interfere with the intended function of the hydrophilic coating, thereby preventing future condensate from forming smooth sheets (as opposed to discrete water droplets) and flowing neatly to the Slurper and to the WS. The small holes in the Slurper plates could also experience some fouling, thus impeding the flow of condensate toward the WS. These events, if they occurred, could result in water being shed from the back of the HX, resulting in entrained water droplets in the downstream ducting. This is a corrosion and contamination concern, in addition to the obvious impediment to accomplishing the humidity control task.

It should be noted that the USL Starboard CCAA HX showed signs of degradation and was replaced by a spare and returned to ground for "Test, Teardown, and Evaluation" (TT&E). Detailed inspection of the HX fins and Slurper confirmed the presence of scale/deposits on the condensing surfaces (see photo in Figure 3), and also showed that there was no appreciable blockage of

the slusher holes. The residue on the HX surfaces rendered those surfaces notably hydrophobic, thus making it very difficult to effectively deliver condensate along the fins and into the Slusher holes to the WS. The scale was not composed of HX coating compounds or materials of construction, but was composed of long-chain fatty acids, silicones, long-chain hydrocarbons, and phthalate esters, all of which can be expected to condense from enclosed manned environments [1].

[insert Figure 3]

Evidence of the Detrimental Affects of HX Wet/Dry Cycling

For the first two years of ISS on-orbit operations, the USL CCAA's were operated predominantly in condensing mode, and in keeping with anti-microbial practices the CCAA's were operated with monthly duty cycles. The inactive CCAA was dried out prior to the month of inactivity. Soon after first activation, the USL Starboard CCAA HX began to exhibit "water carryover" from its fins into the downstream ducting. Water carryover is detected by a Liquid Sensor located in the air duct just downstream from each CCAA. The observed carryover would typically occur within the first five days of each monthly duty cycle, and for the remainder of the month the condensate was more effectively retained by the hydrophilic HX coating.

As condensing operations proceeded in the USL CCAA's over the first few years of ISS on-orbit activities, the Port CCAA HX also began to show possible signs of degradation due to wet/dry cycling. As observed in the Starboard CCAA, the discernable evidence of condensate carryover occurred in the early stages of each new duty cycle. This characteristic behavior is graphically displayed in Figure 4, which shows the percentage likelihood of water carryover on any given day over a typical month of CCAA condensing operations. This figure provides data for the 15 monthly operating periods where water carryover was specifically observed from the CCAA HX (observed during 13 months for the Starboard HX, and 2 months for the Port HX). Note that there have been about 30 months of condensing operations where no water carryover was observed from the active CCAA HX. There were also many months without any condensation in the CCAA (i.e., all humidity control was being accomplished by the Russian THC).

[insert Figure 4]

HX Recovery

The water carryover trend observed in Figure 4 gives rise to the possibility that a residue is left over from each preceding dryout event. This residue interferes with the effectiveness of the condensate collection, distribution, and disposal into the WS. As condensate forms over the course of several days, the residue is dissolved and the hydrophilic nature of the HX fins is somewhat

recovered. The possibility also exists that the size of the small slusher holes could be slightly reduced by the residue, such that condensate flows along the fins and instead of being drawn into the holes it is more likely to become entrained by the air stream into the downstream ducting. At any rate, the first few days of condensing operations appear to dissolve some of the offending materials.

During the ground TT&E performed upon the Starboard HX, attempts were made to remove the accumulated deposits and to recover the HX surface properties. This was first attempted by operating the HX in condensing mode for several days, and then by pouring several solvents through the airside of the HX. After the condensation, and after each subsequent solvent application, the HX was cleaned and re-tested, each time without meaningful improvement to the HX/coating.

It is not clear whether the scale that accrued on the HX surfaces was especially the result of excessive wet/dry cycling, because the anomalous behavior (i.e., the shedding of water from the HX fins into the downstream air ducting) was already occurring before the hardware experienced excessive wet/dry cycling. However, the tendency to carry over was diminished as the CCAA continued to operate in condensing mode, and was exacerbated after the ensuing wet/dry cycle. And while the flow of condensate (i.e., "flushing" the CCAA HX) did not restore the HX coating to an obvious hydrophilic status, the statistics compiled in Figure 4 do suggest some improvement in the process of condensate collection and delivery to the WS.

In an attempt to further visualize the potential recovery benefits of "flushing" the CCAA hardware, Figure 5 presents the frequency of wet/dry cycles as compared to the quantity of condensate-processing events. The figure considers only the Airlock CCAA beginning with the second WS, as the on-orbit data prior to that time frame is more difficult to retrieve. The occurrence of water carryover is overlaid upon this data, thus expressing (or theorizing) the vulnerability to condensate carryover as related to the ratio of wet/dry cycles versus condensate processing events. Note the very low frequency of water processing events throughout the early months, while the wet/dry cycles continued to mount without any means of clearing the accumulating residue. The WS then exhibited water carryover on several occasions. However, the hardware was shown to operate satisfactorily thereafter, even after experiencing many more wet/dry cycles. This information suggests that the hardware can recover and operate successfully, even with the frequent occurrence of wet/dry cycles, provided that there is a regular dose of condensate being processed to counteract the cumulative effect of the wet/dry cycles.

[insert Figure 5]

INTERMITTENT CONDENSATION WITHIN THE WATER SEPARATOR

Complications

The CCAA WS has the function of separating liquid water out from the air/water mixture collected from the CCAA HX Slurper, and delivering that water to the ISS Water Bus. ISS program requirements specify a limit for the percent of air entrainment in the water delivered to the bus, in addition to a maximum particle size limit for the condensate entering the bus. The first of these requirements is addressed by providing a mechanical Check/Relief Valve at the interface to the Water Bus. The cracking pressure of this valve ensures that the water level at the pitot tube inlet (which feeds the valve and the Water Bus) is great enough to ensure a mixture comprising nearly 100% water.

A 25-micron filter is installed in the WS to protect the downstream Check/Relief Valve and Water Bus from particulate matter. A Solenoid Valve is also included in the water circuit, to close and thereby prevent backflow of water from the bus back into the WS when the WS is turned off.

During normal condensing operations, water from the HX (which contains dissolved HX coating and construction materials, and condensed airborne compounds, as already described) is processed without incident through the WS components. However, under intermittent condensing conditions, scale and deposits can accrue as the water repeatedly dries off from the WS surfaces. The circuitous passageways through the filter, pitot tube, Check/Relief Valve, etc., render the WS prone to clogging from deposits after numerous wet/dry cycles occur. These deposits constrict the water passageways such that water eventually carries over into the air exit stream rather than into the Water Bus. The air exit stream is shown in Figure 1; the airflow exits the WS at the bottom of the cutaway schematic, and travels back into the THC ducting near the exit of the CCAA.

In addition to fouling the water passageways, the residue/deposits can accrue on the Check/Relief Valve and Solenoid Valve surfaces. This prevents proper closure of the valves, and either allows water to backflow from the Water Bus into the WS (i.e., when the WS is off and the valves should be closed), or allows some air to enter the Water Bus through a partially-open Check/Relief Valve.

Evidence of the Detrimental Affects of WS Wet/Dry Cycling

Early in ISS operations, the Airlock (A/L) CCAA was particularly prone to wet/dry cycles, as clearly observed by the slope of the graph in Figure 2.c. The A/L CCAA tended to operate with minimal heat/humidity loads, and often was only briefly wetted during the peak crew working hours of each day. A small amount of condensate would form, laden with the various HX/coating compounds, and then would dry out on the

HX and in the WS, leaving behind the accumulating residue.

As seen in Figure 2.c, the A/L CCAA accumulated over 60 wet/dry cycles in the first 500 days of A/L operation, as opposed to the USL Port and Starboard CCAA's which accumulated fewer than 20 cycles apiece during the first 500 days of USL operation. Within the first year of A/L operations, the A/L WS began to carry-over condensate into the air exit stream. After about two years the WS was replaced, and about two years later the replacement WS also exhibited the same symptoms of water carryover. No water carryover has yet been observed in the USL CCAA WS's

Figure 6 shows the occurrences of water carryover in the A/L CCAA WS's, superimposed upon the running total of wet/dry cycles for each of the three WS's used in the A/L thus far. This figure suggests that wet/dry cycles, or more specifically the rapid accumulation of wet/dry cycles, renders the WS hardware susceptible to water carryover.

[insert Figure 6]

WS Recovery

The ability of the CCAA WS to process condensate without carrying over was observed to improve during periods of sustained condensation, similar to the phenomenon observed with the HX in Figure 4. The correlating data is not as clean for the A/L, since the A/L CCAA tends to have brief condensation periods rather than the sustained duty cycles of the USL CCAA's. This tendency to process condensate more effectively later in a sustained condensation period suggests a similar trend with the HX carryover phenomenon, and a similar mechanism for partially cleaning off the fouled surfaces as condensate processing continues.

After the first A/L CCAA was returned to ground for TT&E (late in 2002), it was discovered upon opening the WS that scale accumulation was pervasive on every wetted surface internal to the WS. A series of diagnostic tests pinpointed the blockage at the 25-micron filter. Interestingly, the filter was not clogged by particulate matter, and in fact surprisingly few particles were observed on the filter. Instead, the filter substrate had essentially "grown closed" by the repeated deposits of layers of residue each time that a charge of condensate dried out. In a sense, the filter became a 20-micron filter after a number of wet/dry cycles, and then later became a 15-micron filter, etc., until eventually there was an insufficient passageway to accommodate the processing rate of the condensate.

Other WS passageways, such as the small pitot orifice leading to the Water Bus, were observed during the TT&E to be smaller by some percentage, but not enough to present significant obstruction. This is observed in the micro-photograph of the pitot opening in Figure 7 [2]. The brand new pitot tube would be shiny brass, and the

present ragged appearance shows accumulation of scale but no major obstruction.

[insert Figure 7]

As the WS TT&E progressed to characterize the degree of condensate flow blockage, it became increasingly difficult to duplicate the blocked flow condition, until eventually the full specification condensate flow of 20 lbs/hr was processed by the WS without signs of water carryover into the exiting air stream. It was discovered that the delivery of condensate (or in this case, DI water) had essentially cleaned the filter by re-dissolving the accumulated deposits (salts/minerals/etc.). This discovery during the 2002 TT&E gave increased credence to the possibility of deliberately “flushing” the CCAA to provide a steady stream of condensate through the WS. Of course the on-orbit condensate is not DI water, and thus the capacity of the condensate to dissolve the solids is diminished by the quantity of dissolved material already in solution as the water exits the HX and enters the WS. Because the condensate is typically not saturated after a modest residence time on the HX, there is always expected to be some capacity to receive additional dissolved materials from the internal WS surfaces, and particularly from the 25-micron filter.

It should be noted that a deliberate “flush” of the A/L CCAA is difficult to accomplish due to the sporadic crew presence in that module. Contrast this with the continual crew presence in the USL throughout a typical on-orbit day, which allows a USL CCAA “flush” to be accomplished simply by setting a lower coolant temperature. For the A/L it is also necessary to decrease the cabin temperature setpoint to invoke additional airflow through the HX, and then to augment the cabin humidity by placing wet towels in proximity of the THC Return Ducting. This requires dedicated crew time, and is intrinsically undesirable except under special circumstances. As such, this approach has been used sparingly, but successfully, particularly to support ensuing operations where the crew would be isolated within the A/L and it was necessary to “guarantee” satisfactory CCAA performance.

Also note that consideration is being given to a design modification where the pore size of the WS filter (currently 25-micron) would be increased somewhat to accommodate a greater degree of deposition. This would presumably not prevent the clogging from occurring, but would allow for more wet/dry cycling before the blockage becomes significant. This would help both in the initial deposit accumulation and in the degree of recovery realized with each CCAA “flush”. Considering the relative difficulty of performing a “flush” of the A/L CCAA, such a design modification could prove to be effective.

CONCLUSION

Intermittent periods of condensation within the ISS CCAA's, punctuated by dry conditions within the

CCAA's, are shown to promote the deposition of residue each time that the condensate dries out. The condensate contains salts/minerals/compounds which originate in the CCAA HX or in the air traveling through the HX. As layers of deposits accumulate on the HX and WS surfaces, performance of the HX and WS is shown to degrade.

The effect of wet/dry cycling on the HX is that a residue remains on the HX fin and Slurper surfaces each time that the condensate dries out. This residue interferes with the special hydrophilic coating applied to the HX/Slurper surfaces. Droplets of condensate are thus more prone to sliding off the end of the Slurper and into the downstream ducting. In the WS, the residue from the condensate accumulates until the passageways through the 25-micron filter begin to close off, such that the full complement of condensate cannot be processed and some condensate carries over into the air exit stream. This phenomenon was documented by performing TT&E upon two A/L WS's which were returned to ground after exhibiting degraded performance on-orbit. Again, these droplets of condensate enter the ducting downstream from the CCAA.

After the second on-orbit A/L WS was replaced, a new protocol was established for the USL CCAA's, where a deliberate “flush” is performed upon a USL CCAA every time that another 4 wet/dry cycles have occurred without significant condensate being processed. The long-term benefit of this “flush” has yet to be confirmed, but is expected to be especially effective in restoring the WS, as observed in ground testing during TT&E.

One CCAA HX has been returned to ground over the first six years of ISS on-orbit operations. While on-orbit behavior showed more effective processing of condensate by this specific HX after sustained condensing operations, ground tests performed during the HX TT&E did not show appreciable dissolution of the accumulated residue.

The negative effects of wet/dry cycling can be avoided to some degree by deliberately selecting operating conditions to reduce the rate at which wet/dry cycling occurs. This is accomplished most readily by selecting the coolant temperature through the CCAA HX to either promote continuously wet or continuously dry conditions. In the case of the A/L CCAA, which is often not needed for extended periods (even for several weeks at a time), the decision was made after the first WS replacement to deactivate the CCAA whenever practical. This proved to be advantageous, and as observed in Figure 6 this shift in operating philosophy may have quadrupled the on-orbit life for the second A/L WS. (The third A/L WS is not experiencing that advantage, as the A/L CCAA has had a much higher duty cycle recently due to increased A/L operations.)

By the combined approach of: 1) preventing or minimizing wet/dry cycles, 2) “flushing” the CCAA's to

recover some functionality after excessive wet/dry cycling, and 3) invoking design changes to become more accommodating of wet/dry cycling, the overall ISS THC System is successfully adapting in order to achieve continued satisfactory performance in a transitory on-orbit environment.

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CONTACT

Roger von Jouanne received his Bachelor's (1982) and Master of Science (1984) degrees at Southern Illinois University, in the field of "Mechanical Engineering and Energy Processes". Roger has been a Christian since 1980, was married in 1984, and has worked for The Boeing Company on the International Space Station Program since 1984. He and his wife, Pam, have three children from ages 13 to 21. Roger can be contacted at 'roger.g.vonjouanne@boeing.com'.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

A/L: ISS U.S. Airlock.

CCAA: Common Cabin Air Assembly; the air conditioner for the U.S. modules of the ISS.

Dewpoint: A measure of the quantity of water vapor contained within air or other gases. If a surface temperature (e.g., temperature of a HX fin) drops below the dewpoint, then dew or condensate will form upon that surface.

DI Water: De-ionized Water; water which is essentially free from dissolved ionic compounds or atoms.

HX: Heat Exchanger; a subassembly within the CCAA.

Hydrophilic: Having an affinity for water. A droplet of water placed onto a hydrophilic surface will spread out to become a thin film.

Hydrophobic: Repelling water. A droplet of water placed onto a hydrophobic surface will remain nearly spherical and will readily roll or slide along that surface.

IMV: Intermodule Ventilation; deliberate interchange of atmosphere between different ISS modules.

ISS: International Space Station.

LTL: Low-Temperature-Loop; water loop providing coolant to a variety of ISS System and Payload users.

RS: Russian Segment; comprises the Russian modules of ISS.

THC: Temperature and Humidity Control.

TT&E: Test, Teardown, and Evaluation; a relatively standard sequence of investigative events following a hardware failure.

U.S.: United States.

USL: United States Laboratory Module.

Wet/Dry Cycle: A period of wet or condensing conditions within CCAA hardware followed by dry conditions.

WS: Water Separator; a subassembly within the CCAA.

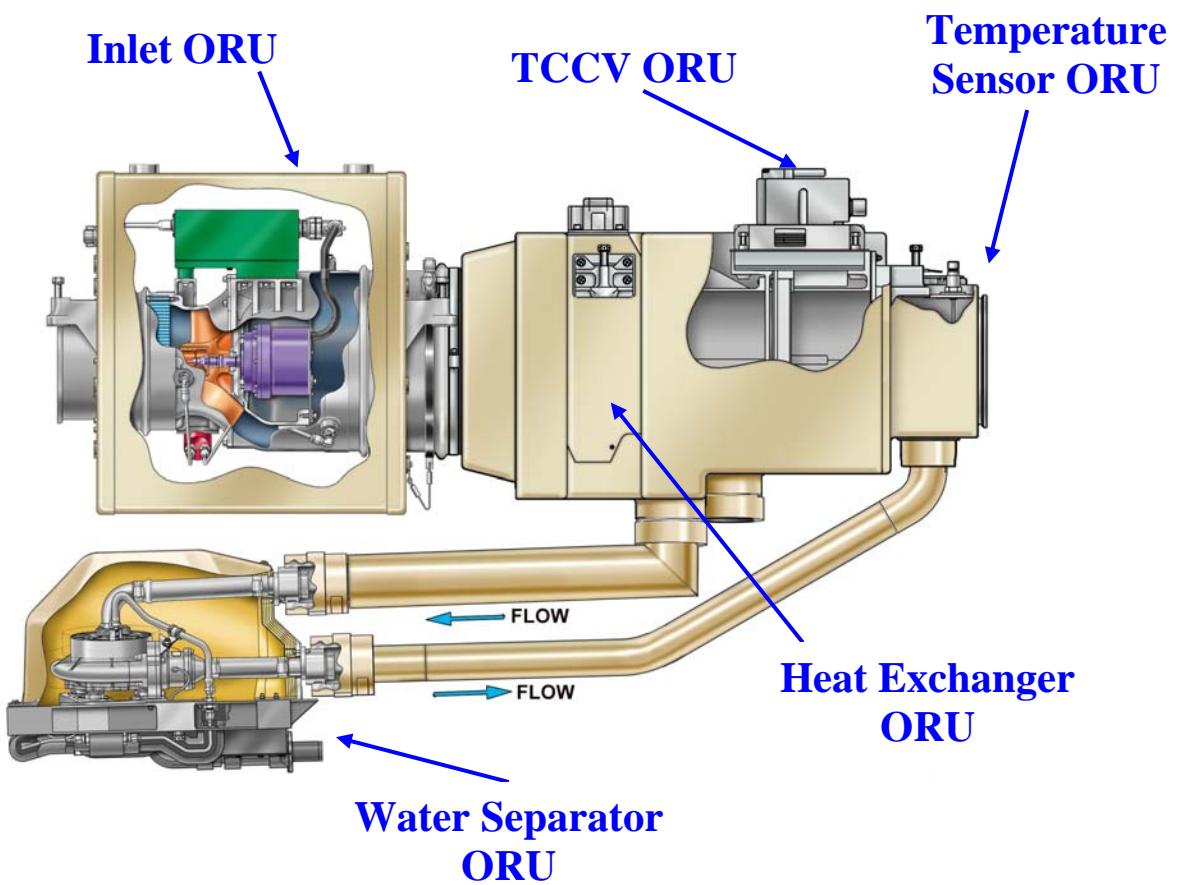


Figure 1 Simplified Cutaway Schematic of CCAA

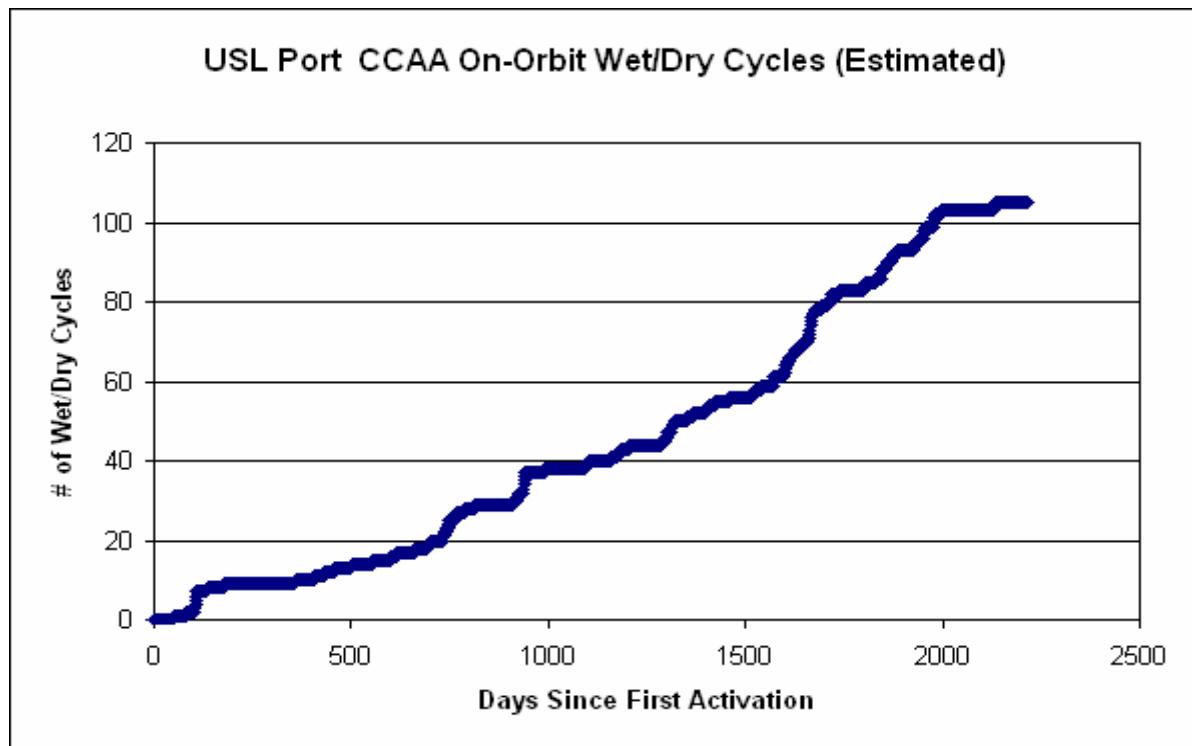


Figure 2.a History of USL Port CCAA Wet/Dry Cycles

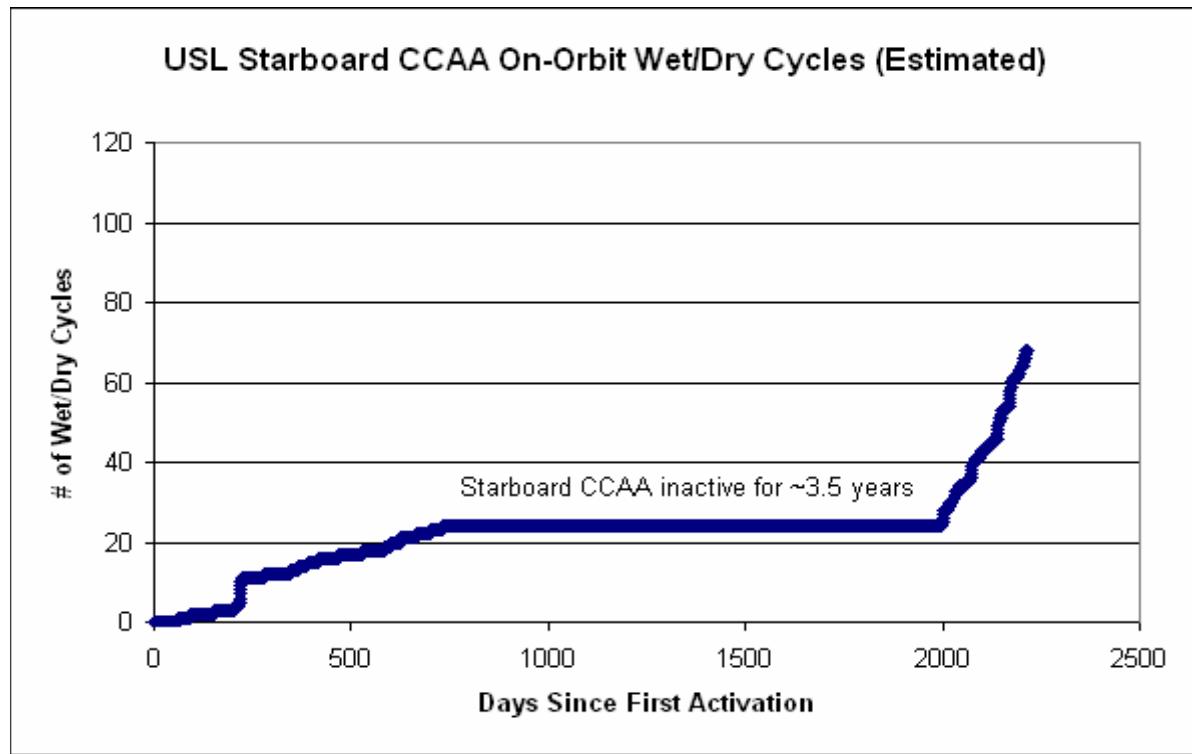


Figure 2.b History of USL Starboard CCAA Wet/Dry Cycles

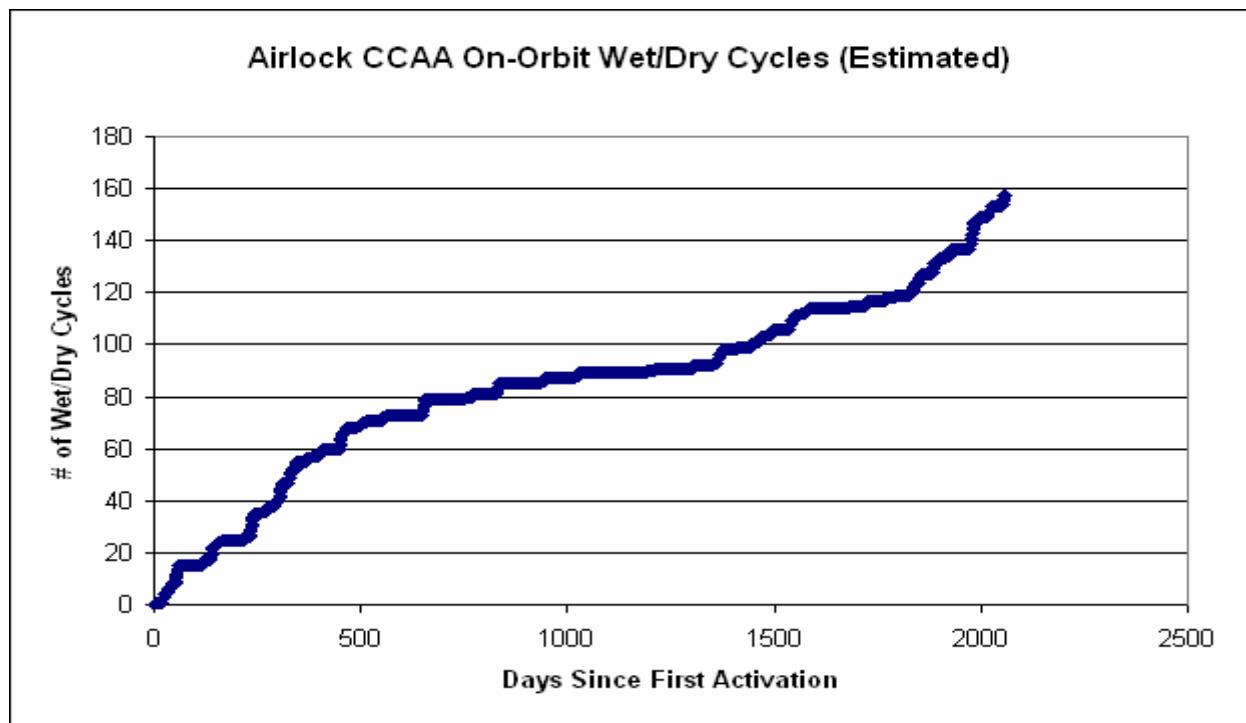


Figure 2.c History of Airlock CCAA Wet/Dry Cycles

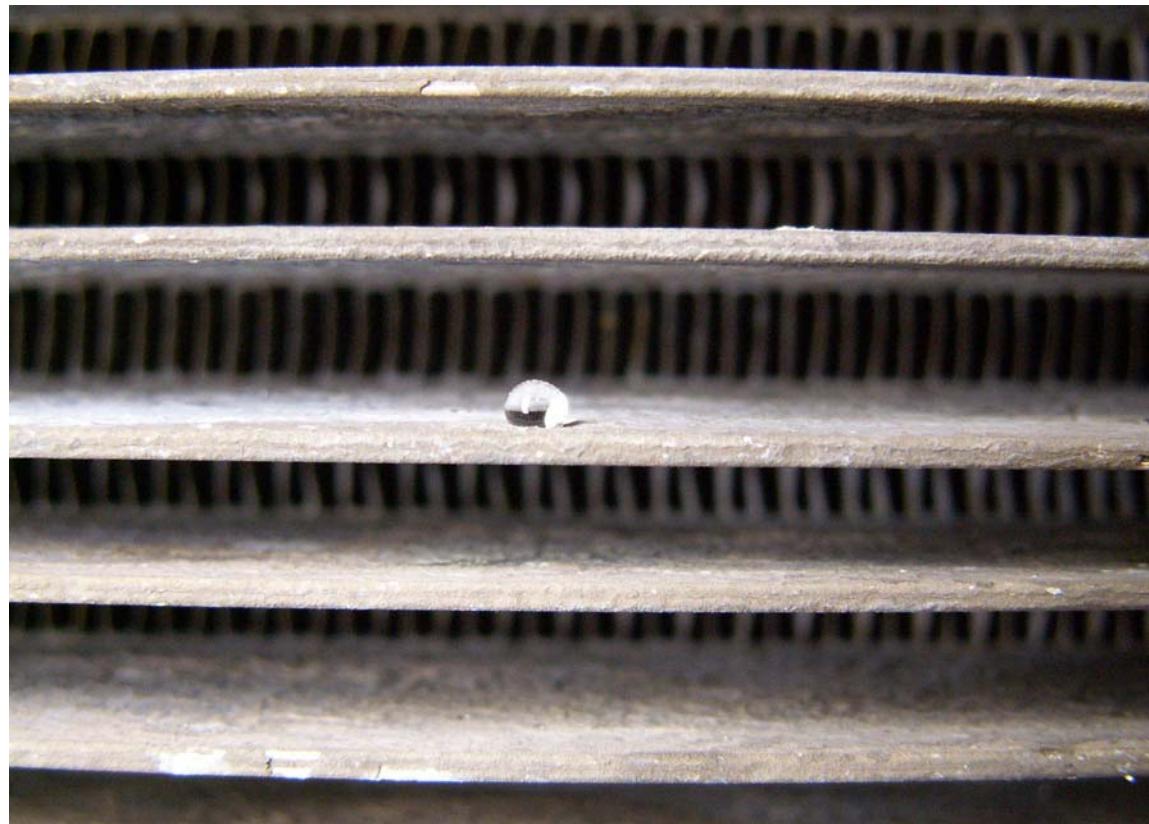


Figure 3 TT&E Photo Looking Into the Back of the Stbd CCAA HX;
Note Residue/Deposit, and Observe Water Droplet on Hydrophobic Slurper Plate at Exit of HX Fins

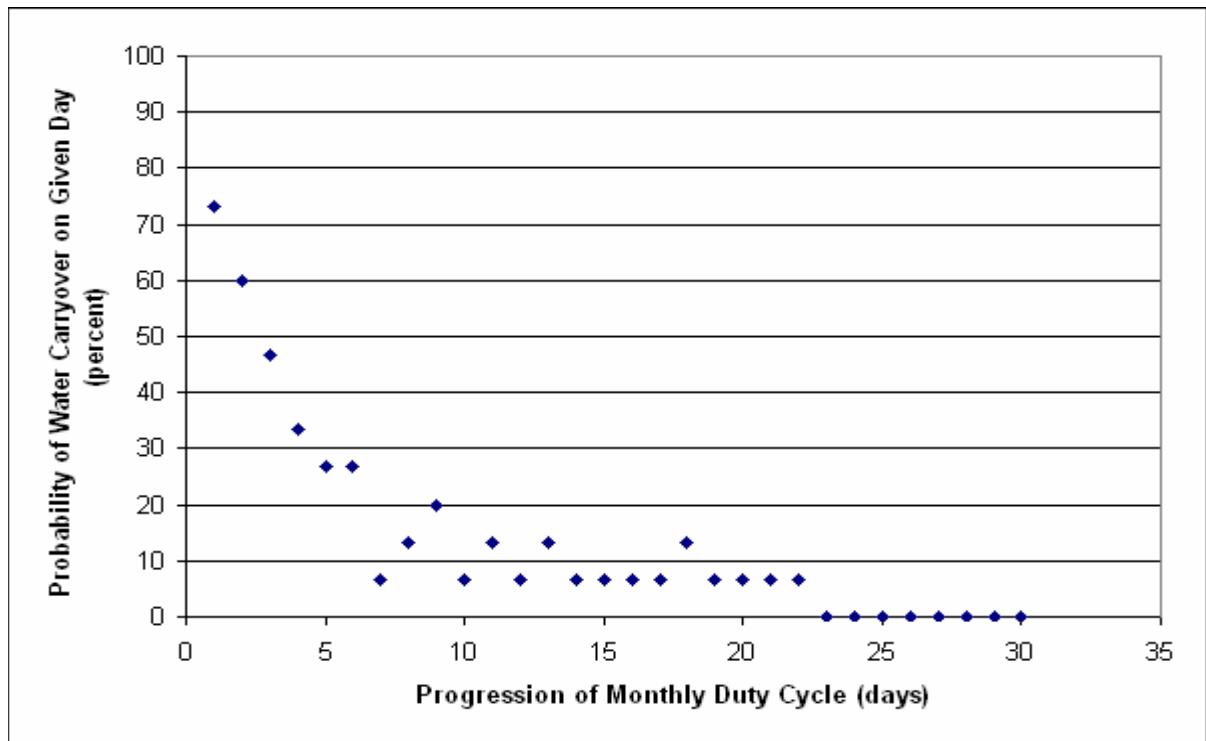


Figure 4 Profile of HX Water Carryover Occurrences Through Typical Monthly Duty Cycle

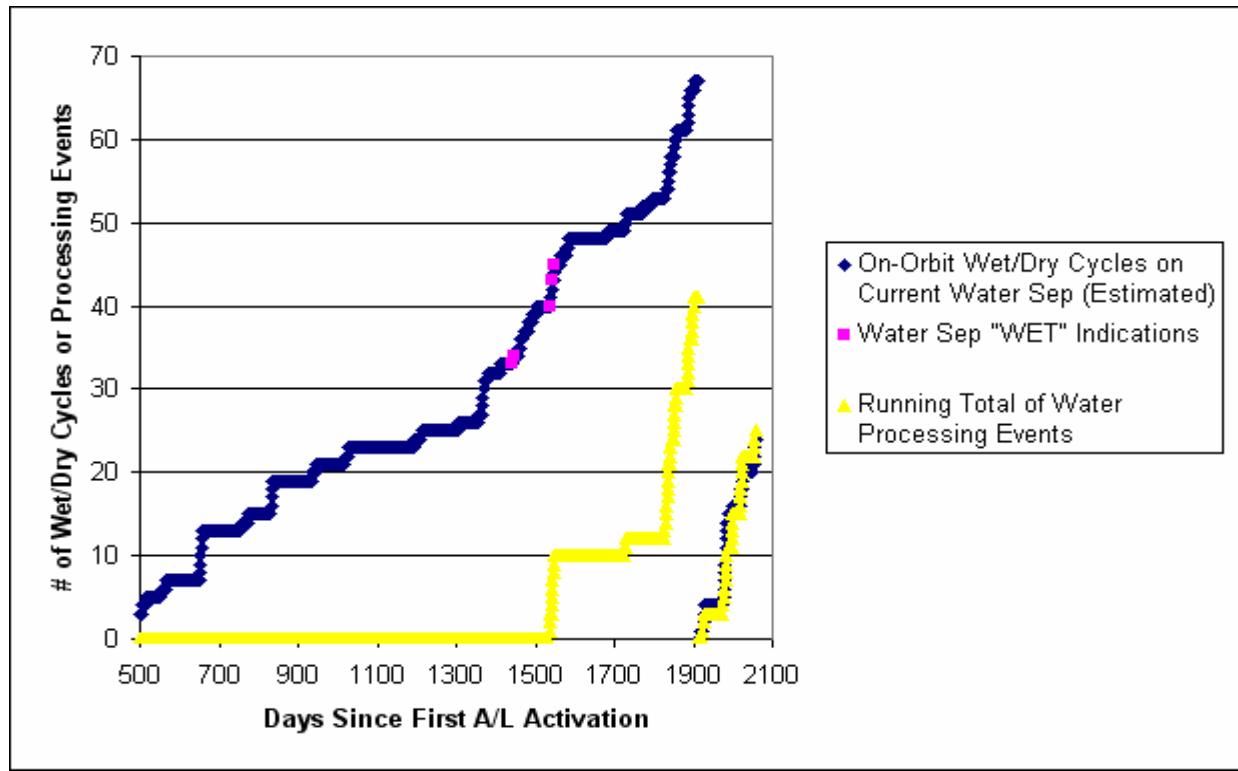


Figure 5 General Assessment of the Accrual of Detrimental Deposits on CCAA WS,
Expressed as the Ratio of Wet/Dry Cycles to Water Processing Events

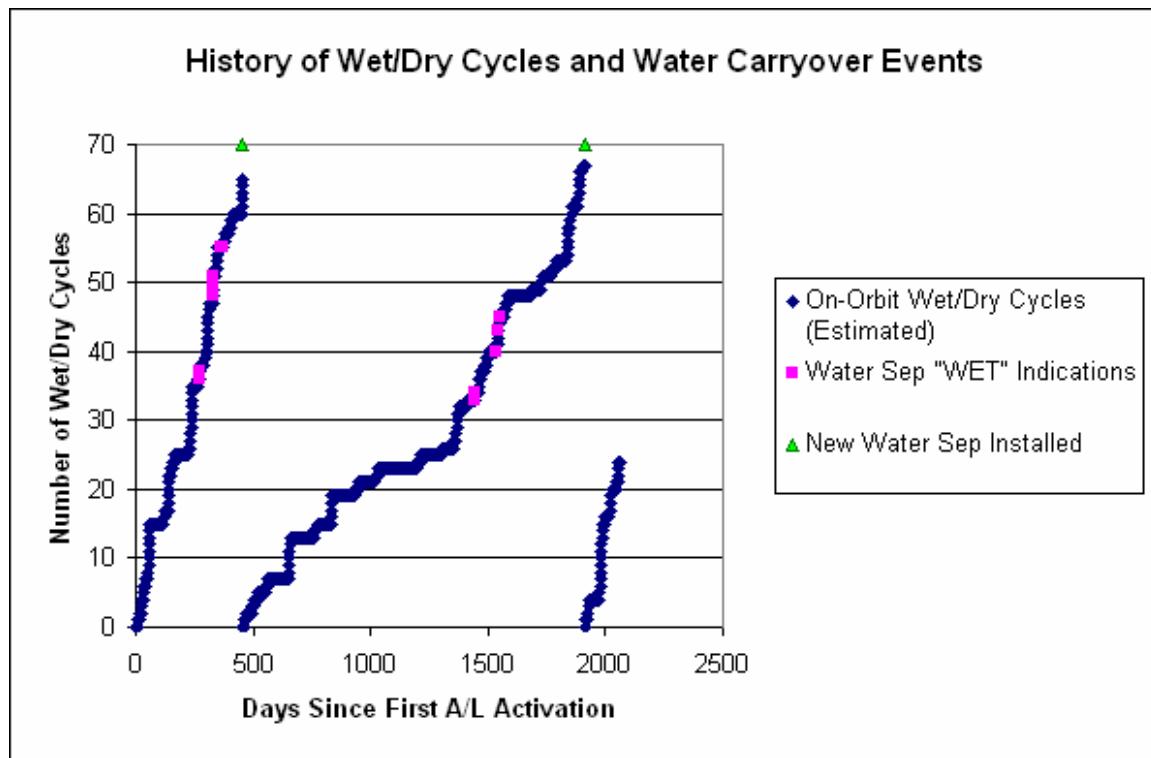


Figure 6 Airlock CCAA Water Carryover from WS as Related to Frequency of Wet/Dry Cycles



Figure 7 Airlock WS TT&E Photo Showing Accumulation of Scale at Pitot Inlet